



Low Carbon Propulsion Strategic Thrust Overview



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NASA Aeronautics Research Six Strategic Thrusts



Safe, Efficient Growth in Global Operations

- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks



Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard



Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance



Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology



Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system

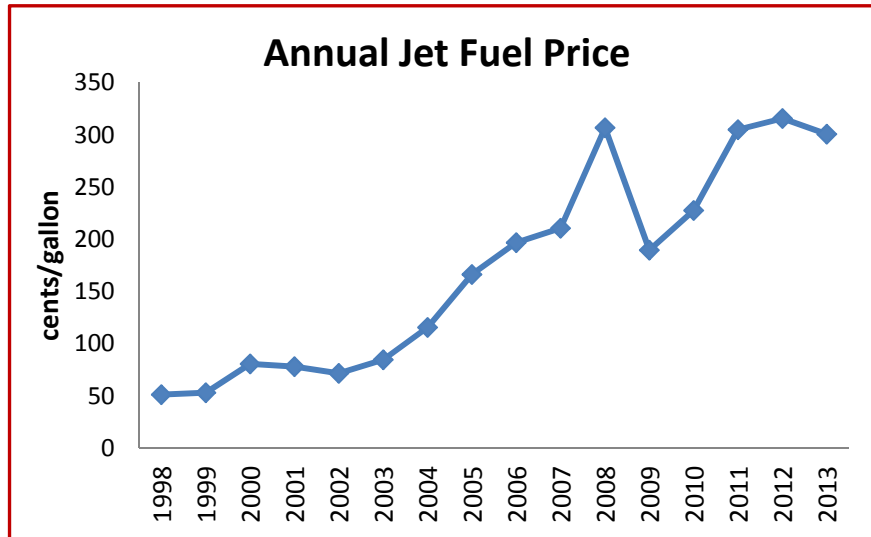


Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

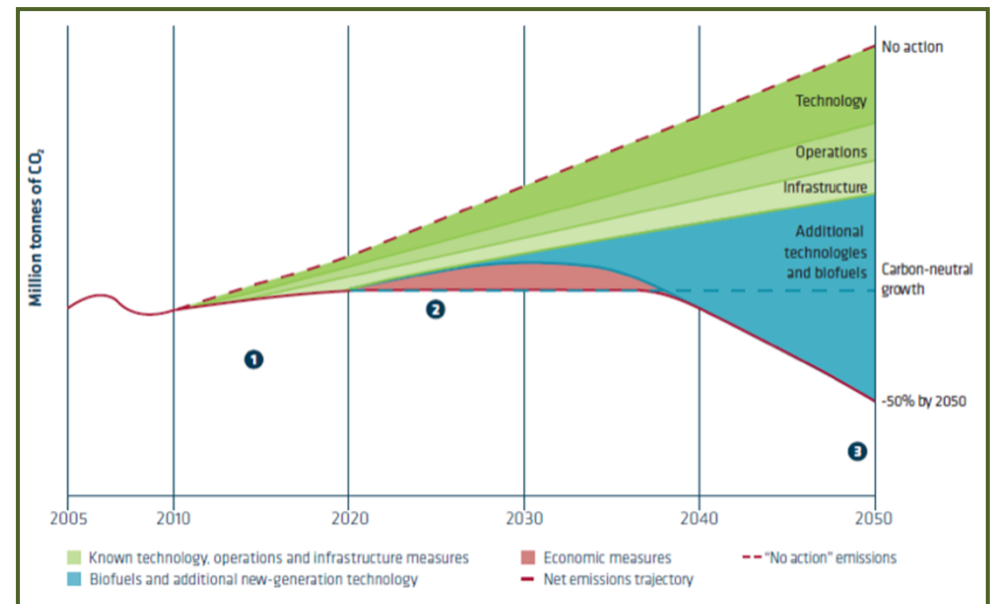


Low Carbon Energy Background



- Jet-fuel price volatility
- Global oil demand growth despite limited production and supply
- National security threat from foreign energy dependence
- Aviation environmental impacts estimated at 2% GHG

- The aeronautics industry has committed to ambitious GHG reduction goals
- Aviation energy independence is a key goal of policy makers
- Aviation alternatives to oil may provide significant economic benefits during the next century





Transition to Low-Carbon Propulsion Thrust

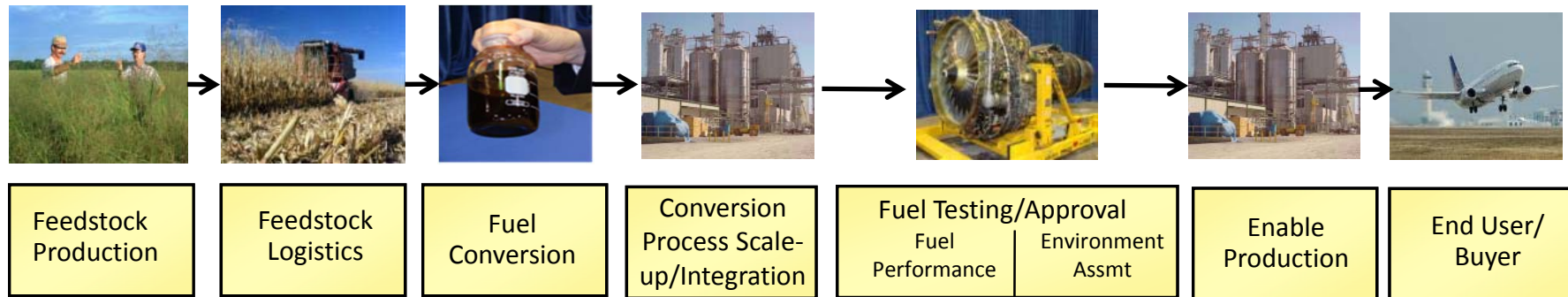
There are two primary focus areas:

1. Characterization of Alternative Fuels
 2. Pioneering new Propulsion Concepts/ Cycles
- Most current content supporting this Thrust is in the FW/AATT Project with two Technical Challenges:
 - **Alternative Fuel Emissions at Cruise:** Fundamental characterization of a representative range of alternative fuel emissions at cruise altitude (completed in FY15)
 - **Electric Motor Power Density:** Achieve a 2X increase in the power density of an electric motor (expected to be revised to increase scope)
 - Other FW/AATT TCs support (e.g. advanced core and configurations)
 - Some foundational work is in the TAC Program AS/TTT Project (e.g. combustion modeling)
 - Potential growth opportunities exist in the TAC Program CAS Project too, which may also transition to the AAVP or IASP portfolios.
 - There is a close synergy between Thrust 4 and Thrust 3 (Ultra Efficient Vehicles) – Advanced propulsion cycles needed for ultra-efficient vehicles will also be critical for low carbon propulsion systems)



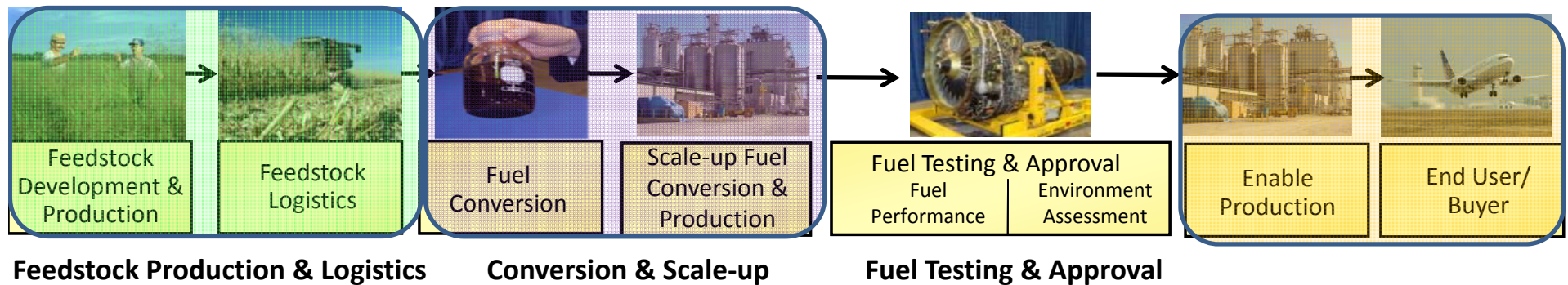
Characterization of Alternative Fuels

Alternative Jet Fuels Supply Chain – Agency Coordination



USDA	✓	✓	✓	✓	---	✓	✓	✓
DOC	✓	---	✓	✓	✓	✓	---	✓
DOD	---	---	---	---	✓	✓	✓	✓
DOE	✓	✓	✓	✓	---	✓	✓	---
EPA	---	---	---	---	---	✓	✓	---
FAA	---	✓	---	✓	✓	✓	---	✓
NASA	---	---	---	---	✓	✓	---	---
NSF	✓	✓	✓	---	---	---	---	---

National Alternative Jet Fuel Strategy Under Development



Strategy Document

Organization and Development of Subgoals & Objectives

- Three thematic topic sections
 - Feedstock Production and Logistics
 - Fuel Conversion and Scale-up
 - Fuel Testing & Approval (including certification and qualification)
- Cross-cutting section – considerations that span entire supply-chain or the interfaces
- Categorized objectives along three time horizons: Near- (<5 years), Mid- (5-10 years) & Far- (>10 years) term - similar to National Aeronautics R&D Plan
- Acknowledge non-R&D context of policy (e.g., RFS), economic factors/challenges, & international considerations

Contributing Departments & Agencies
Agriculture, Commerce, Defense, Energy,
EPA, FAA/DOT, NASA, NSF, State

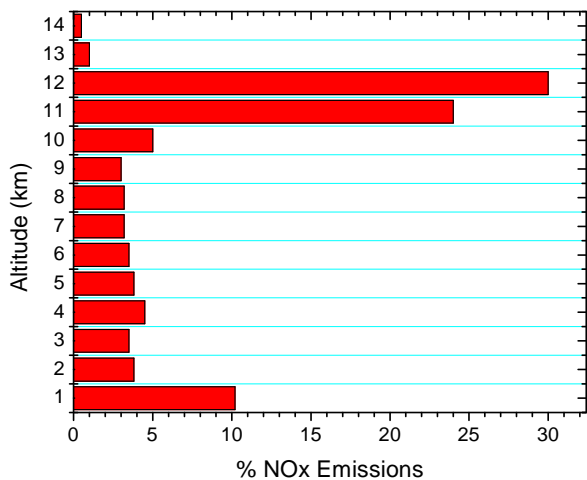
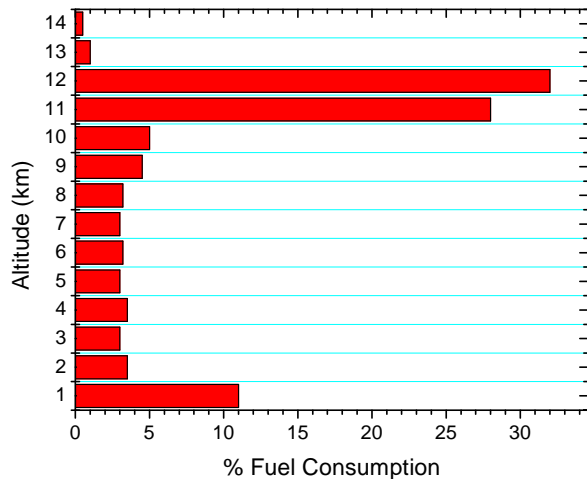
NASA Alternative Jet Fuel Characterization Research



- **Laboratory tests** to determine alternative fuel combustion and emissions characteristics
 - High-pressure flame-tube experiments on LDI fuel injectors—ongoing
 - High-pressure tests on GE & PW sector rig combustors
- **Ground-based engine tests** to evaluate alternative fuel effects on emissions under real-world conditions
 - PW308—March 2008
 - AAFEX-I—January 2009
 - AAFEX-II—March 2011
- **Cloud chamber tests** to examine PM effects on contrail formation
 - ACCRI/FW Tests—2010—2015
- **Airborne experiments** to evaluate fuel effects on emissions and contrail formation at cruise
 - **ACCESS-I: Feb-April, 2013**
 - **ACCESS-II: May, 2014**



Motivation for Flight Experiments



- Almost 90% of jet fuel burned during flight
- Cruise-level power settings are very poorly simulated in ground tests; altitude test cell operations are expensive and can't reproduce atmospheric mixing processes
- Particle emission parameters are very temperature dependent--ground-level tests cannot replicate the cold, dry conditions present at flight altitudes
- Emission impacts on contrails cannot be assessed at ground level
- Very little data available to relate ground-based particulate matter (PM) emission parameters to cruise altitude emissions; data for black carbon mass/number emissions are particularly lacking
- Very little data available to relate aircraft PM emissions to contrail formation and microphysical characteristics

- Ground-based emissions impact local air quality
- Cruise emissions impact climate



Were ACCESS-2 Objectives Met? (GRADE)

1. Establish fuel and thrust effects on emissions at cruise and the relationship between ground and cruise black carbon emission indices (A+)

High quality emissions data were obtained behind both inboard engines at 3 different power settings and 5 different altitudes for both fuels. Ground emission data were also successfully recorded. Relationship between ground and cruise being addressed through collaborative modeling

2. Examine the impact of contrail processing on aerosol emission indices (B)

High quality aerosol emissions data recorded for both fuels with and without contrails; analysis should reveal effects of ice particle scavenging on aerosol # and size. Very limited far field data obtained to examine aerosol characteristics in evaporating contrails.

3. Investigate the relationship between Black Carbon (BC) #/size and ice particle characteristics as a function of ambient conditions (B)

Lots of near-field data recorded within contrails to examine soot/ice links, may be limited by probe sensitivity to small ice particles. Would have benefited by having more data in persistent contrails.

4. Investigate the role of fuel sulfur in volatile aerosol and contrail formation at cruise (B+)

Obtained extensive emissions data with engines burning < 10 ppm S blend and 525 ppm S JP-8; differences in aerosol # and sulfate mass quite apparent. Analysis should reveal role of sulfur in regulating contrail ice formation. Would have benefited by having more data in persistent contrails.

Highly persistent contrails encountered on single flight, thus limited data on contrail aging



Were ACCESS-2 Objectives Met? (GRADE)

5. Obtain contrail measurements in flight corridors (C)

HU-25 developed engine problems plus we exhausted most of our flight hours doing formation flights, were unable to conduct missions from LaRC at conclusion of field mission.

6. Obtain detailed wake turbulence measurements for model validation (A)

T-33 recorded 3-D winds during dozens of wake vortex crossings in nearfield behind DC-8; HU-25 and Falcon 20 measured turbulence and 3-D winds in far-field contrails.

Things We can Brag About

- Established successful techniques for sampling aircraft exhaust and contrails in the near and far-field behind DC-8, can be extended to other flight venues (Eco-Demonstrator, ECLIF, etc.)
- Obtained one-of-a-kind, extensive, high quality data set of NO_x, CO, aerosol and Black Carbon emission indices for a typical commercial airliner at cruise — will be highly valuable for model development and aviation air quality/climate impact assessments.
- Obtained first direct measurements of contrail El_{ice} at cruise altitudes
- Developed highly productive collaborations with DLR and NRC, will pay off in future flight opportunities

Aeronautical Sciences Project Combustion Research



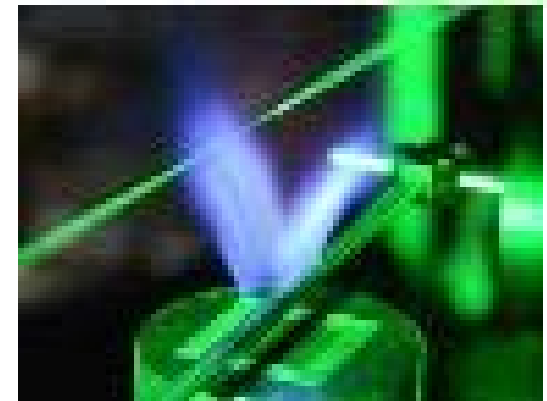
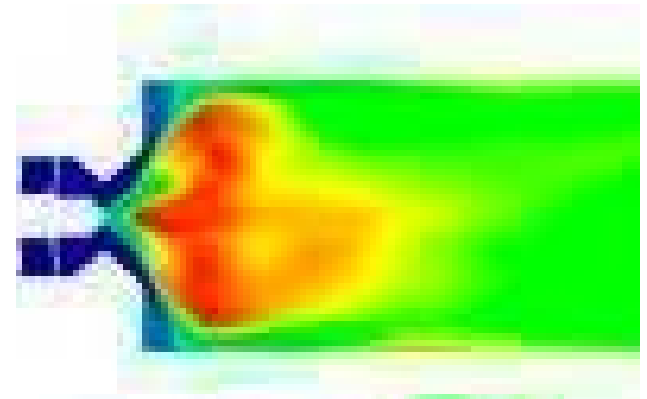
Develop and validate physics-based combustion models, perform fundamental experiments and investigate new combustor technologies

Goal

- Improved capability to design combustor concepts that have the potential to meet NASA emissions goals for future aircraft engines.

Approach

- Develop and validate physics-based combustion models for CFD
- Perform CFD validation experiments to provide high-quality data at relevant conditions (fuel, pressure, temperature)
- Perform experiments to provide fundamental understanding of low-emission systems (e.g., Lean Direction Injection)
- Develop and test passive & active combustion control technologies
- Explore new combustor technologies (e.g., Pressure Gain Combustion)





Foundational work that benefits the characterization of alternative fuels

- *Develop/validate physics-based combustion models for CFD* → Given fuel properties and a chemical kinetics mechanism, validated tools can provide quantitative assessment of impacts of fuel changes to given combustor design/operating condition
- *Perform CFD validation experiments to provide high-quality data at relevant conditions (fuel, pressure, temperature)* → GRC Test Cell SE-5 is intended to test surrogate liquid fuels (3-5 known hydrocarbon components) for detailed CFD validation data rather than complex (and less well-defined) jet fuels or alternative fuels
- *Perform experiments to provide fundamental understanding of low-emission systems* → GRC Test Cell CE-13 is designed to support jet fuel and alternative fuel testing (up to 5 atm flame-tube pressure).
- AS Combustion Lead participated in development of FAA-funded National Jet Fuels Combustion Program solicitation (July 2014 release) and will participate in review of proposals.



Pioneering New Propulsion Concepts/Cycles



Why Now and Why NASA?

- Electric propulsion systems for aircraft will enable national environmental and fuel burn reduction goals to be met
- N+3/N+4 studies have identified promising aircraft and propulsion systems
- Power system development for land-based applications does not adequately address thermal or mass management requirements for aerospace applications
- Builds on NASA's core competencies bringing together researchers from multiple centers working multi-disciplinary problems
- NASA research lowers the technical risk and accelerates the development for advanced propulsion systems
- Research aligned with ARMD strategic R&T thrusts of transition to low-carbon propulsion and ultra-efficient commercial vehicles
- While there is a new focus on hybrid technologies, NASA continues advanced turbine engine research and also explores other potential ideas for low carbon propulsion systems



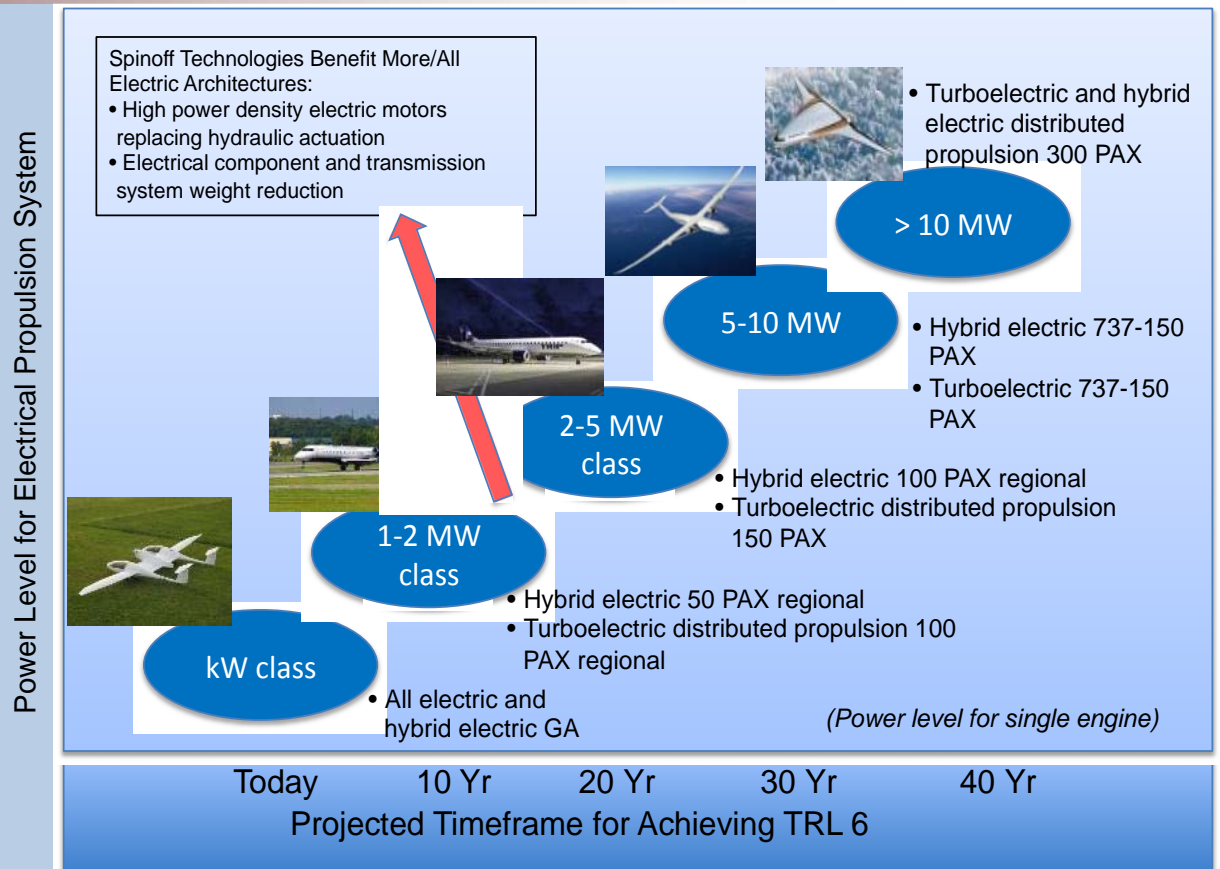
Hybrid Electric Propulsion Systems for Aviation

Low Carbon Propulsion

NASA studies and industry roadmaps have identified hybrid electric propulsion systems as promising technologies that can help meet national environmental and energy efficiency goals for aviation

Potential Benefits

- Energy usage reduced by more than 60%
- Harmful emissions reduced by more than 90%
- Objectionable noise reduced by more than 65%



What is needed?

- Conceptual designs of aircraft and propulsion systems
- Higher power density generators and motors
- Flight-weight power system architectures and simulations
- Higher energy density energy storage systems (non-NASA)
- Extensive ground and flight testing



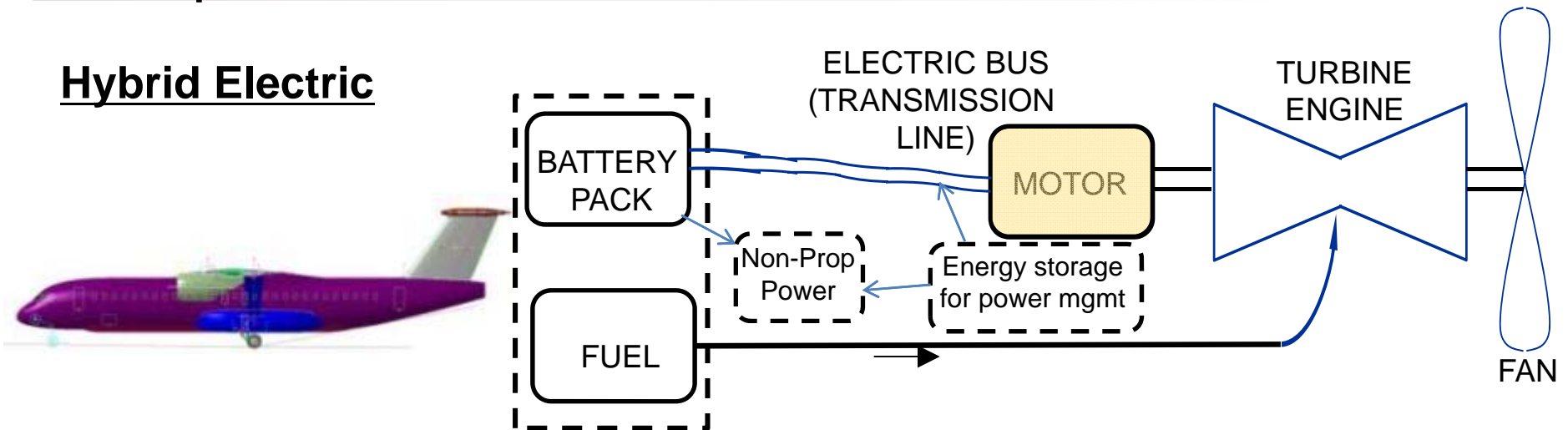
Hybrid Electric Propulsion Systems Objectives

- Technology development will enable radically different propulsion systems that can meet NASA's N+3 goals for subsonic commercial aircraft
- Research will be coordinated across NASA and will leverage external non-NASA investments to focus on key technologies needed to conduct a propulsion system demonstration
- Research portfolio includes long-term objectives with periodic off-ramps of technologies for introduction in aircraft with more- and all-electric architectures
- Current focus on future large regional and single-aisle (Boeing 737-class) aircraft for greatest impact on fuel burn, noise, and emissions, but also exploring vertical lift applications because of their unique mission capabilities.
- Capitalize on validation opportunities at smaller scale when appropriate.

Possible Future Commercial Large Transport Aircraft

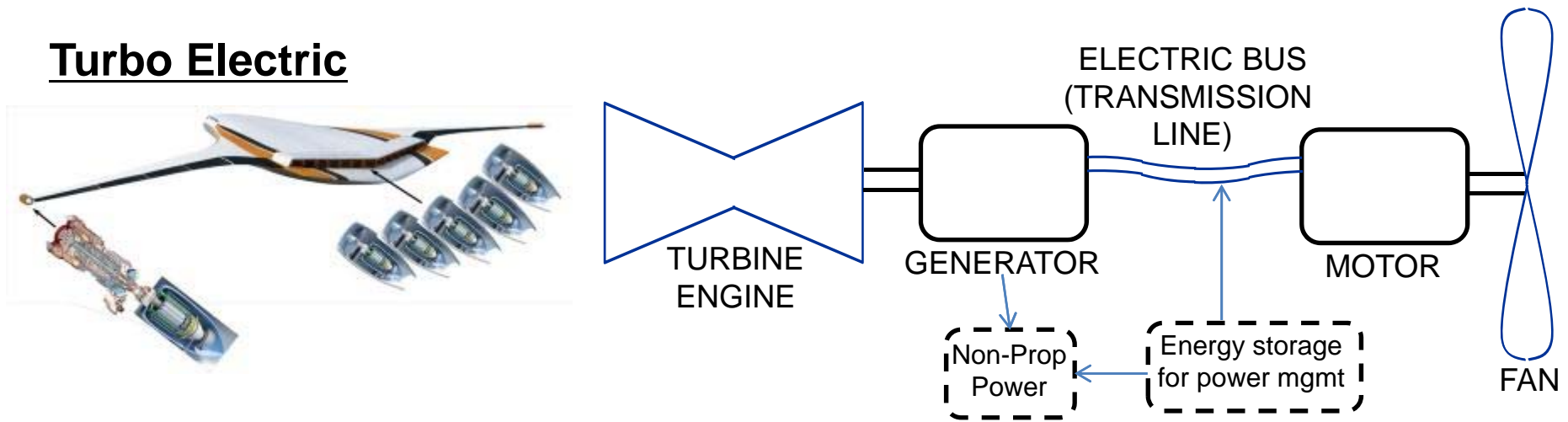


Hybrid Electric



Both concepts can use either non-cryogenic motors or cryogenic superconducting motors.

Turbo Electric



Benefits Estimated from Fixed Wing Studies

SUGAR (baseline Boeing 737, 2008 technologies)

- ~60% fuel burn reduction
- ~53% energy use reduction
- 77-87% reduction in NOx
- 24-31 EPNdB cum noise reduction



N3-X (baseline Boeing 777-200)

- ~63% energy use reduction
- ~90% NOx reduction
- 32-64 EPNdB cum noise reduction





Partnership Strategies

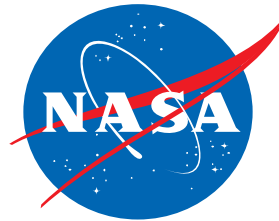
Comprehensive partner strategies are very important for all aspects of the Low Carbon Propulsion Thrust. Examples include:

- Cross-Agency coordination on a new Alternative Jet Fuel Strategy that also involves engaging the external community
- Multi-Agency and international participation on key experiments (ACCESS)
- Under NASA's lead, the alternative jet fuel work has been the first substantial focus area for collaboration under the International Forum for Aviation Research (IFAR).
- Inspiration for surge in focus on hybrid systems for larger aircraft are borne out of NASA Advanced Concept Studies (internal and external).
- New partnerships with traditional partners (e.g. coordinating with Navy to leverage their efforts on more-electric systems for ships).



Summary

- NASA is taking a leadership role with regard to developing new options for low-carbon propulsion.
- Work related to the characterization of alternative fuels is coordinated with our partners in government and industry, and NASA is close to concluding a TC in this area.
- Research on alternate propulsion concepts continues to grow and is an important aspect of the ARMD portfolio
- Strong partnerships have been a key enabling factor for research on this strategic thrust.





Backup Charts

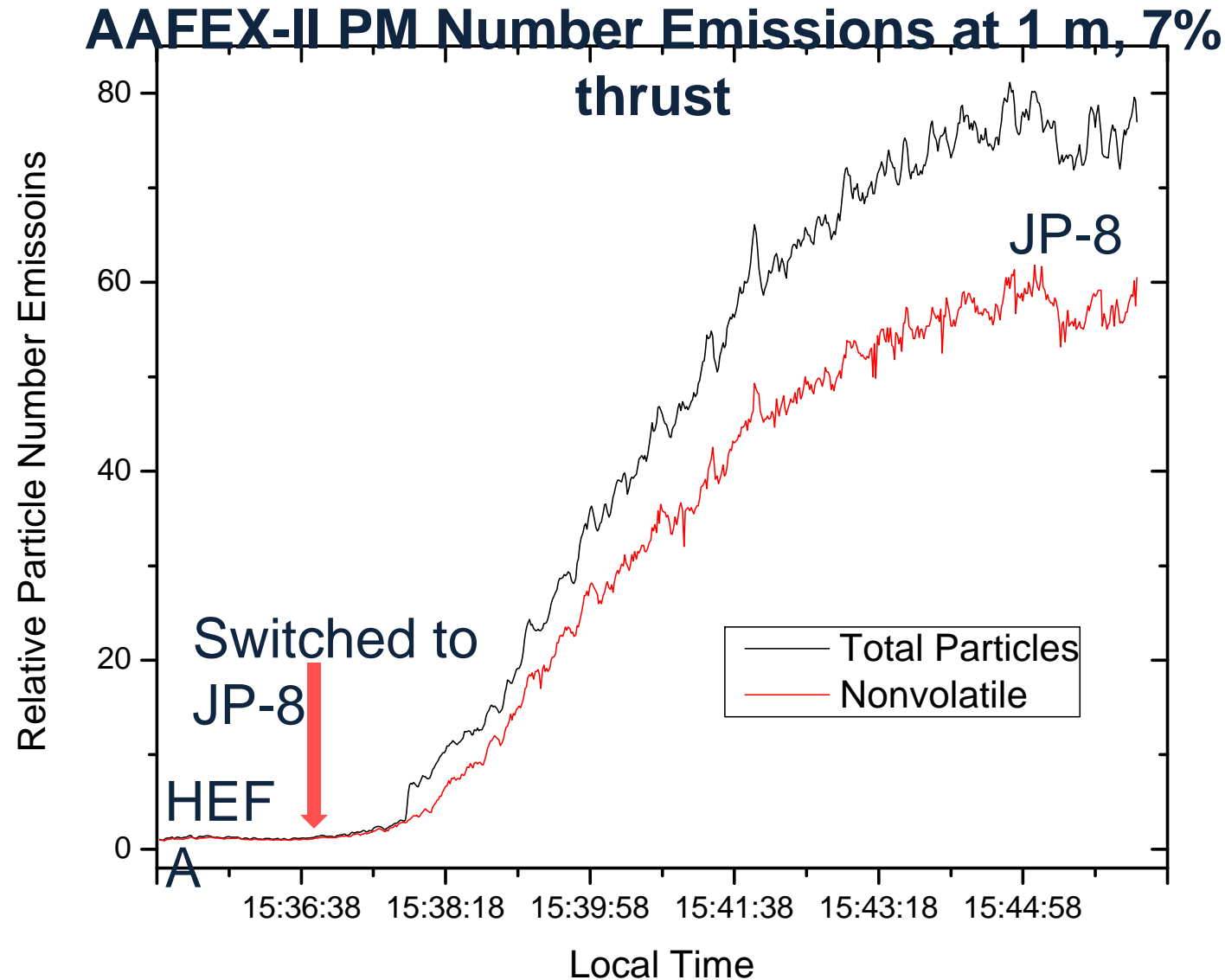
Motivation to Develop Alternative Jet Fuels



- Fuel prices have increased dramatically in the last 10 years and now represent the largest operational expense to airlines—alternative fuel sources needed to drive down costs.
- U.S. imports a large fraction of its fuel—greater domestic production needed to increase fuel security (especially a concern of U.S. military)
- Many airports are located in heavily polluted areas which cannot meet clean air standards—cleaner burning fuel needed to reduce air quality impacts
- Aviation accounts for a significant fraction of green-house gas emissions and air travel is increasing—renewable fuels needed to reduce aviation climate impacts

President Obama is placing great emphasis on alternative fuel development for all energy needs

Alt Fuels Profoundly Reduce PM Emissions



Differences in PM ratios due to volatile particles associated with

Progression of Electric Technology for Commercial Transport Aircraft (NASA Projection)



	Conventional	More Electric Architecture	All Electric Architecture	Hybrid Gas Turbine-Electric Propulsion		Electric Propulsion
				“Turboelectric Distributed” Gas Turbine Power, Decoupled Distributed Electric Propulsors	“Hybrid Electric” Gas Turbine and Electric Dual Power, Coupled Propulsor	
				Ambient Temperature or Cryogenic and Superconducting		
Propulsive Power Source	Gas Turbine	Gas Turbine	Gas Turbine	Gas Turbine + Electric	Gas Turbine + Electric	Electric
Non-Propulsive Power Source	Gas Turbine	Gas Turbine + Electric	Gas Turbine + Electric	Gas Turbine + Electric	Gas Turbine + Electric	Electric
Generation	< N	N, N+1	N+2,N+3	N+3, N+4		> N+4
		Current industry focus is on more/all electric architectures for commercial transports		Recommended NASA Investment Target (with likely adoption of common technologies for more/all electric architecture in N+2/N+3 timeframe)		



Physics-Based Combustion Models

OBJECTIVE

Improve capability of combustion CFD to accurately predict emissions for advanced low emissions combustion concepts operating on a variety of fuels.

APPROACH

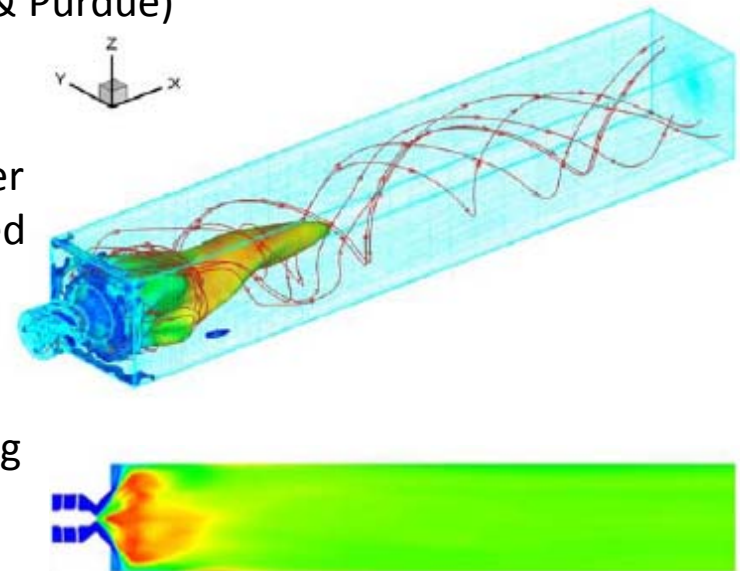
- Time Filtered Navier Stokes (comparable to LES)
- Turbulent combustion modeling (Linear Eddy Mixing & Scalar FDF adapted for TFNS)
- Liquid fuel atomization/vaporization models; Soot models
- Radiation heat transfer (full spectrum k-distribution; Penn State NRA)
- Polyhedral Meshing /Adaptive Mesh Refinement
- Open NCC development (Version 1.0 beta test release Oct 2014)
- Combustion dynamics - NRAs (Georgia Tech & Purdue)

ACCOMPLISHMENTS

- Time-Filtered Navier Stokes (TFNS) with non-linear subfilter models for momentum, energy & scalar transport validated by experiments for confined swirling non-reacting flows
- TNFS with Linear Eddy Mixing and Scalar Filtered Density Function models for turbulence-chemistry interaction assessed against experiments for confined swirling reacting flows.

SIGNIFICANCE

Improved and validated physic-based combustion models to help design combustors that meet challenging new emission standards at higher pressure conditions





Combustion CFD Validation Experiments

OBJECTIVE

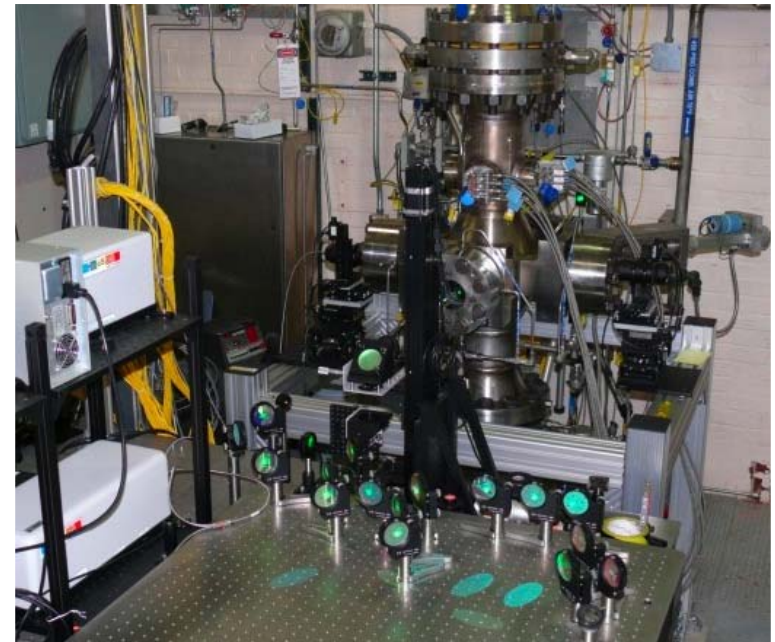
Provide spatially & temporally resolved measurements of major species, temperature, velocity, & drop size (liquid fuel) data for gaseous & liquid fuels in a single element LDI configuration under a variety of operating conditions (up to 250 psi) for validating CFD models/codes.

APPROACH

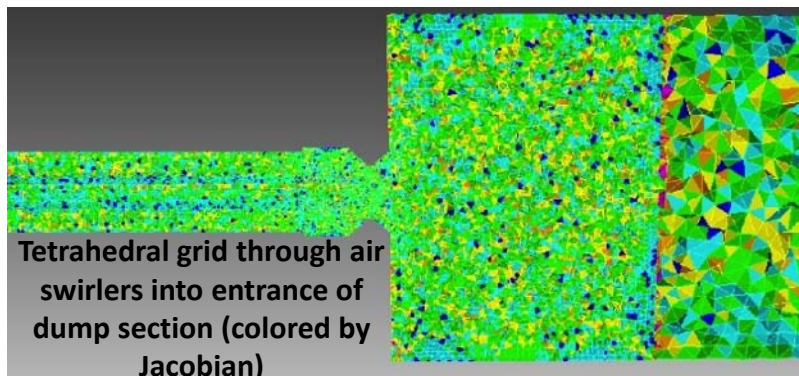
- High-pressure test cell (SE-5) at NASA Glenn
- Non-proprietary single element LDI configuration to provide a swirl-stabilized reacting flow
- Laser Doppler Velocimetry (LDV) (velocity measurements)
- Phase Doppler Particle Analyzer (PDPA, drop size measurements)
- High Frequency dual sub-frame burst gating (SBG) Raman spectroscopy (major species & temperature)
- Fuels: gaseous (CH_4/H_2 blend), single-component liquid (n-heptane), multi-component liquid (jet-A surrogate)

SIGNIFICANCE

High-quality experimental data at high pressure conditions and using configurations representative of future lean burning systems to validate physic-based combustion models for designing future combustors.



SE-5 High Pressure Combustion Lab & Flame Data from Single Element LDI gaseous fuel test





CFD Vision 2030

GRAND CHALLENGE PROBLEM 2:

Off-design turbofan engine transient simulation. This case encompasses the time-dependent simulation of a complete engine including full-wheel rotating components, secondary flows, combustion chemistry and conjugate heat transfer. This GC will enable virtual engine testing and off-design characterization including compressor stall and surge, combustion dynamics, turbine cooling, and engine noise assessment. Similar to GC 1, demonstration of advances in accurate prediction of separated flows, complex geometry, sliding and adaptive meshes, and nonlinear unsteady flow CFD technologies will be required to achieve this goal. In addition, advances in the computation of flows of widely varying time scales, and the predictive accuracy of combustion processes and thermal mixing, will be necessary.

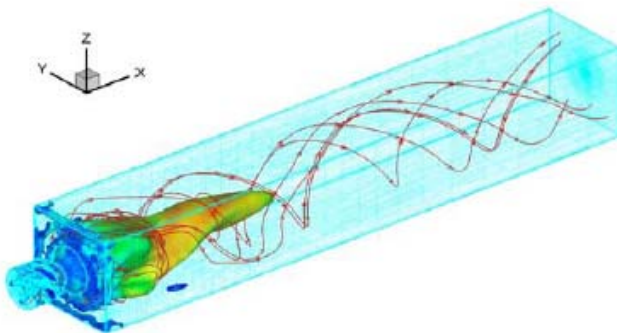
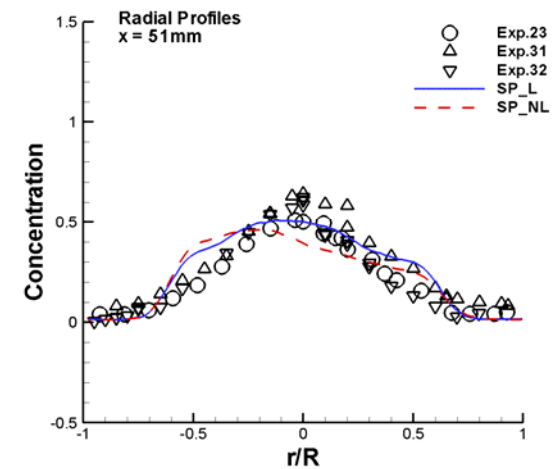
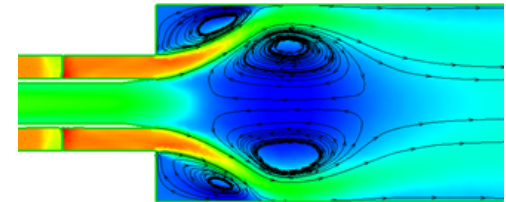
In the area of turbulent reactive flows, investment needs to continue towards the development of a validated, predictive, multi-scale combustion modeling capability to optimize the design and operation of evolving fuels for advanced engines. The principal challenges are posed by the small length and time scales of the chemical reactions (compared to turbulent scales), the many chemical species involved in hydrocarbon combustion, and the coupled process of reaction and molecular diffusion in a turbulent flowfield. Current combustion modeling strategies rely on developing models for distinct combustion regimes, such as non-premixed, premixed at thin reaction zone, and so forth. The predictive technology should be able to switch automatically from one regime to another, as these regimes co-exist within practical devices. Furthermore, research should continue into methods to accelerate the calculation of chemical kinetics so that the CFD solution progression is not limited by these stiff ordinary differential equations (ODEs). The deep research portfolios of DoE and the US Air Force can be leveraged to further these modeling needs.

Physics-Based Combustion Models

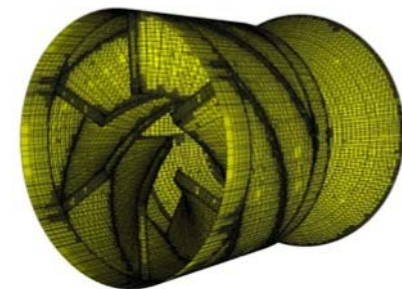
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TNFS with Linear Eddy Mixing and Scalar Filtered Density Function models for turbulence-chemistry interaction assessed against experiments for confined swirling reacting flows.



Polyhedral mesh with hanging nodes coding completed and tested.





CFD Validation Experiments

ACCOMPLISHMENTS

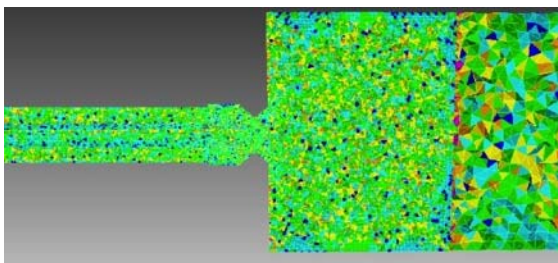
Completed calibration matrix enables quantitative measurements using SBG Raman

Dual-SBG Raman demonstrated at sampling rates of 10 kHz for measuring temperature and species concentrations in a lean gaseous CH₄/H₂ flame

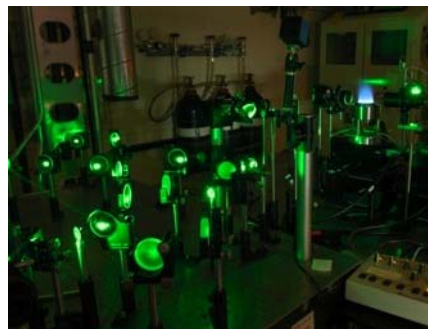
SBG Raman featured on cover of December 2013 issue of the Photonics Spectra journal.

Patent on new Raman detection using a special camera architecture called frame-transfer CCD

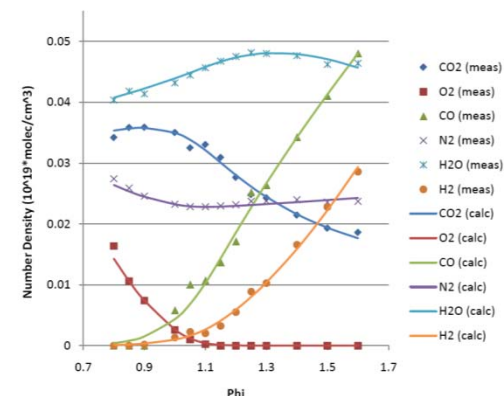
CFD grids and sample inlet conditions provided to UTRC and Delft University of Technology as part of a Collaboration effort.



Slice showing tetrahedral grid through air swirlers into entrance of dump section (colored by Jacobian)



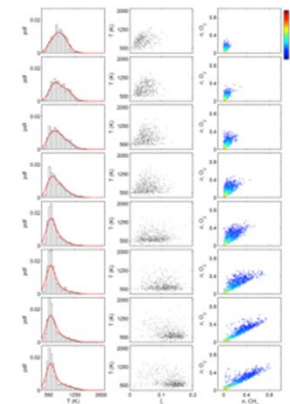
Raman Calibration Facility



and Calibration Flame Data



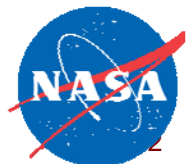
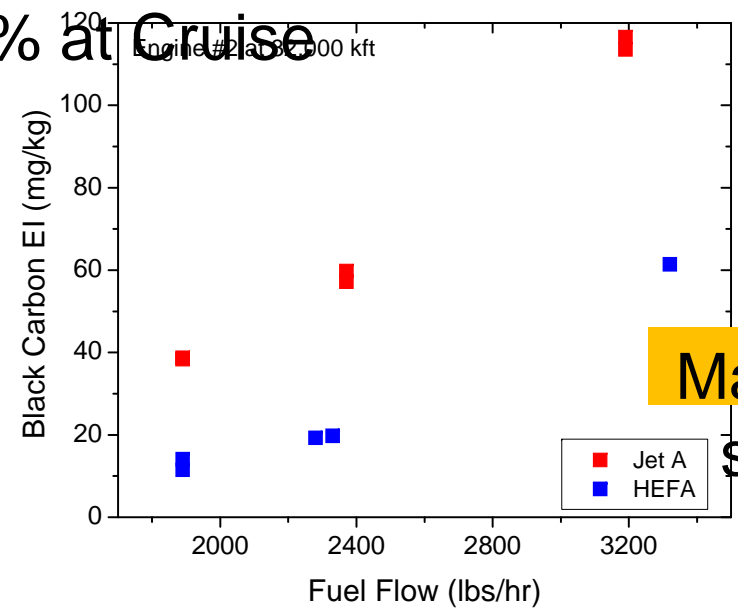
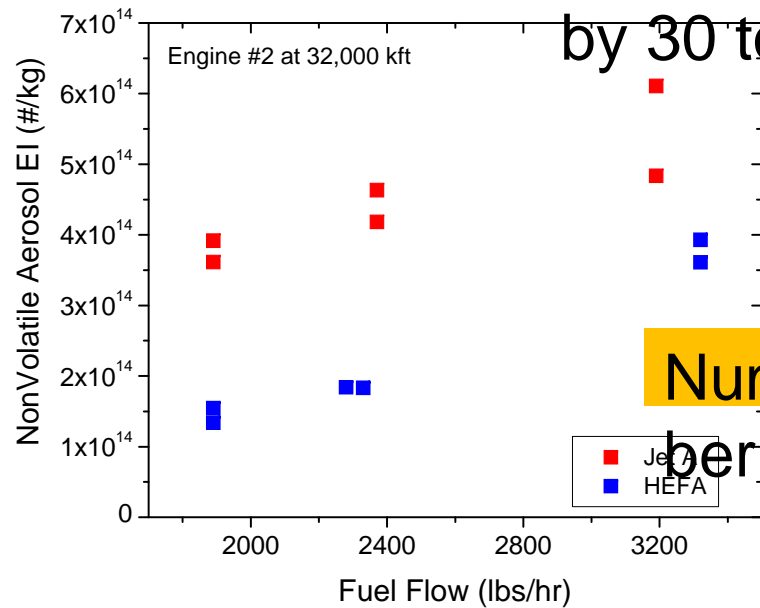
SE-5 High Pressure Combustion Lab and
Flame Data from Single Element LDI gaseous fuel test



Preliminary Results



HEFA Blend Reduces Black Carbon Number and Mass Emissions



ACCESS Also Included Ground Test Measurements

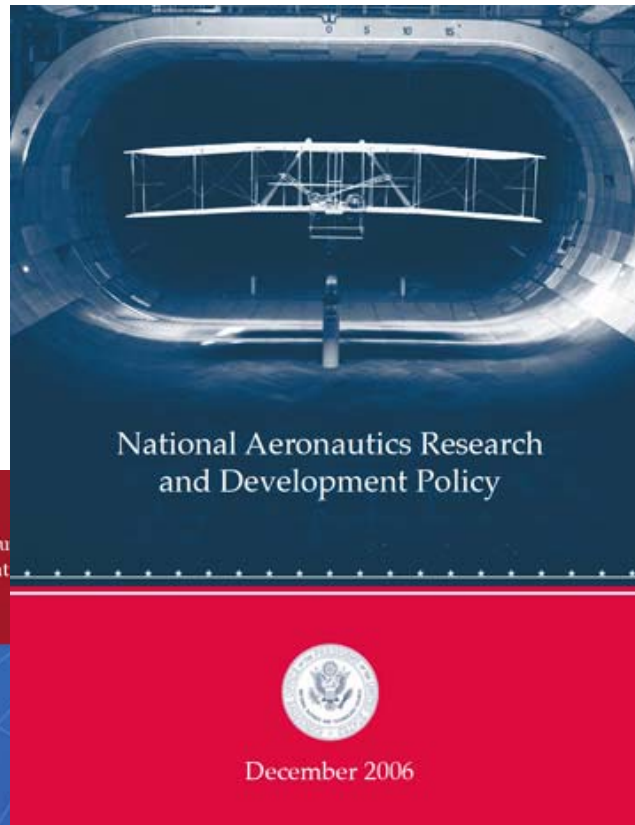


Enabled additional measurements, power settings, and

- Probe stands mounted at 30 m behind both inboard engines
- Falcon instrument payload + the mobile laboratory with additional instruments (shown at right)
- Cycle through fuels, power settings over an approximately 4-hr. experiment



Background: National Aeronautics R&D Plan



Developed under sponsorship of the National Science & Technology Council, Aeronautics S&T Subcommittee (ASTS)

Plan focuses on 17 aeronautics goals in four areas –

- Mobility
- Security
- Safety
- Energy Availability, Efficiency & Environmental Protection
 - Goal 1: “Enable new aviation fuels derived from diverse & domestic resources to improve fuel supply security & price stability”



- Success requires communication & coordination across a set of Agencies & stakeholders broader than the traditional aeronautics community.
- Workshop is part of a broader coordination process across federal Agencies with input from the non-federal sector resulting in an Alternative Jet Fuels R&D Strategy.